

Reducing maintenance costs in agreement with CNC machine tools reliability

A L Ungureanu¹, G Stan¹ and P A Butunoi¹

¹„Vasile Alecsandri” University of Bacau, Department of Industrial Engineering,
Calea Marasesti Street, No.157, 600115, Bacau, Romania

E-mail: chirila_ana_bc@yahoo.com

Abstract. Aligning maintenance strategy with reliability is a challenge due to the need to find an optimal balance between them. Because the various methods described in the relevant literature involve laborious calculations or use of software that can be costly, this paper proposes a method that is easier to implement on CNC machine tools. The new method, called the Consequence of Failure Analysis (CFA) is based on technical and economic optimization, aimed at obtaining a level of required performance with minimum investment and maintenance costs.

1. Introduction

Optimizing maintenance strategies in line with the CNC machine tools reliability is a difficult step, because reliability is a criterion for obtaining performance, but becomes a restriction by setting a minimum threshold of reliability ensured by maintenance actions.

Keeping maintenance strategy in line with reliability elements is an issue that led to several ways of achieving a level of required performance with minimum investment and maintenance costs.

In his work, Doostparast M [1] adopted a model for planning preventive maintenance actions using a computerized simulation algorithm that provides decision-making solutions to maintain a certain level of reliability with minimal cost. In the proposed approach, the planning horizon is divided into pre-specified control periods, during which one of these three actions must be performed: simple control, preventive repair or preventive replacement.

A method for optimizing the periodicity of the technical and economic preventive maintenance actions is presented by Remy E [2], through an analysis software called MARS (Maintenance of Repairable Assessment Systems), developed by Grenoble University.

In terms of production process performance, Kans M [3] proposes an optimization of maintenance activities by creating a database in order to provide a clearer picture of the failure scenarios and to help in decision-making maintenance. This database underpins the development of applications for monitoring the performance of the production process, in order to decide the most cost effective maintenance policy or simulation of existing maintenance solutions.

Another point of view is that of Carnero M [4], who proposes a system of assessing the predictive maintenance feasibility, in agreement with the tools belonging to operational reliability. This method uses the hierarchical process analysis where a coefficient is assigned to each process, depending on its complexity and priority, deterministic decision rules and Bayesian tools, all these representing an assessment method used to evaluate the need to implement this type of maintenance.



But all the above-mentioned methods require a laborious calculation or acquiring software that can be costly. To simplify the analysis methodology for optimizing maintenance costs in accordance with the CNC machine tools reliability, this paper proposes a method of combinatorial analysis, called CFA (Consequence of Failure Analysis), which includes the method FMEA (Failure Modes and Effects Analysis) FDP (Failure Developing Period) and FA (Financial Analysis).

The new method aims at detecting the non-critical components that must be isolated in the preventive maintenance actions, to allocate only the strictly necessary human resources and save financial resources.

2. Failure Modes and Effects Analysis (FMEA)

One of the most frequently used methods that analyzes the failure mode and effect on system performance is FMEA [5]. This conventional method uses Risk Priority Number (RPN) to prioritize the risk of damaging the components.

RPN can range from 1 to 1000 and is the mathematical product of three parameters: severity of a failure (S), the probability of occurrence (O) and the detectability (D). A failure mode that shows a higher RPN has priority for a corrective action, compared to other modes of failure with lower RPN values. A detailed scale to rank the severity, occurrence and detection is given for each of these parameters in tables 1, 2 and 3, respectively.

Table 1. Rating scales for severity in FMEA design.

Effect	Severity of effect	Rank
Hazardous	Hazardous without warning. It suspends operation of the system.	10
Serious	Hazardous outcomes with warning.	9
Extreme	The system is inoperable.	8
Major	Product performance is severely affected.	7
Significant	The system is inoperable with minor damage.	6
Moderate	System inoperable without damage. The product needs repairs.	5
Low	The product does not need repairing yet.	4
Minor	System operable with some degradation of performance. The product does not need repairs.	3
Very minor	Very minor effect on product performance.	2
None	No effect.	1

Table 2. Rating scales for occurrence in FMEA design.

Probability of failure	Possible failure rates	Rank
Inevitable	≥ 1 in 2	10
Very high	1 in 3	9
Repeated failures	1 in 8	8
High	1 in 20	7
Moderately high	1 in 80	6
Moderate	1 in 400	5
Relatively low	1 in 2.000	4
Low	1 in 15.000	3
Remote	1 in 150.000	2
Nearly impossible	≤ 1 in 1.500.000	1

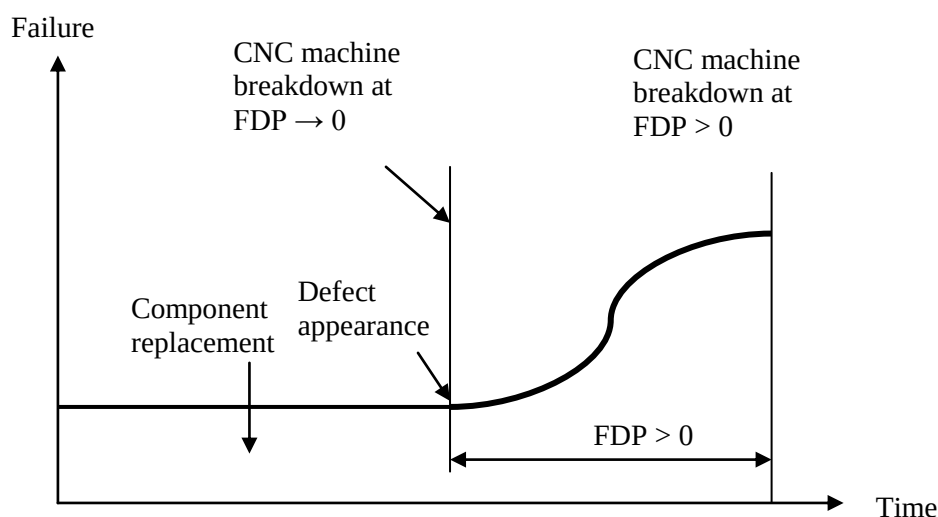
Although FMEA is an effective method, it should be noted that the assessment of critical components analysis takes a long time, and the information obtained is only one of the decision criteria applied to maintenance activities.

Table 3. Rating scales for detection in FMEA design.

Detection	Detection by design control	Rank
Absolute uncertainty	The cause of failure can't be detected.	10
Very remote	Very remote chance of detecting the cause of failure.	9
Remote	Remote chance of detecting the cause of failure.	8
Very low	Very low chance of detecting the cause of failure.	7
Low	Low chance of detecting the cause of failure.	6
Moderate	Moderate chance of detecting the cause of failure.	5
Moderately high	Moderately high chance of detecting the cause of failure.	4
High	High chance of detecting the cause of failure.	3
Very high	Very high chance of detecting the cause of failure.	2
Almost certain	The cause of failure can be detected almost certainly.	1

3. Failure Developing Period (FDP)

FDP represents the time interval between the fault appearance and the interruption in CNC machine tools operation. The figure 1 shows that the defects arising during operation are divided into two categories: defects evolving in time, which can be discovered and thus interruptions in operation may be prevented and defects rapidly evolving, for which failure is inevitable.

**Figure 1.** Defect evolution in time.

When the defect evolution is slow ($FDP > 0$), there is a difference between the point of failure and the interruption in operation. Thus, the remaining lifetime of the components can be approximated, allowing timely intervention of maintenance teams. Applying a reactive maintenance in this case is not an optimal solution, as time allows corrective action planning.

If a malfunction occurs rapidly ($FDP \rightarrow 0$), the corresponding period of time taken in order to find the damage is very short or almost inexistent. In this situation preventive maintenance action may be considered in order to replace the component before failing. However, there is a risk that revisions are made more frequently as necessary, with the possibility of damaging other components during assembly / disassembly. Moreover, the remaining lifetime of the replaced components cannot be easily determined and unnecessary replacements can be carried out.

Application of reactive maintenance is often the best solution when the failure happens randomly, and the cost of lost production until the reinstatement of CNC machine tool does not exceed the cost of applying a preventive maintenance.

4. Financial Analysis (AF)

Assessing the problem from the cost standpoint, 90 % of the decision-making process about the implementation of maintenance procedures is finding the answer to what happens if CNC machine tool fails, what is the cost of effective maintenance (parts and labor), other components that can be affected, the reinstatement time leading to production losses, environmental damage or human casualties.

Reactive maintenance costs (C_{rm}) are made up of actual maintenance allocated costs (C_{am}) and additional costs caused by the malfunction of the CNC machine tool (C_a). For reactive maintenance (M_r), C_a is far higher than that allocated for preventive maintenance.

In conclusion, the total cost of reactive maintenance can be evaluated with the formula:

$$C_{rm} = C_{am} + C_a \quad (1)$$

The specific cost of reactive maintenance (C_{srm}) in unit time is:

$$C_{srm} = \frac{C_{am} + C_a}{MTBF} \quad (2)$$

MTBF is the average time for good operation between two failures.

Preventive maintenance (M_p) involves the replacement of a component at time t , even if it is not broken. If we note by $R(t)$ - the probability that the item will not be damaged before the completion of the time interval t and $F(t)$ - the probability that the item to be damaged prior to the completion interval t , the cost of preventive maintenance C_{pm} is:

$$C_{pm} = C_{am} \times R(t) + (C_{am} + C_a) \times F(t) \quad (3)$$

The specific cost of preventive maintenance (C_{spm}) in time unit is:

$$C_{spm} = \frac{C_{am} \times R(t) + (C_{am} + C_a) \times F(t)}{MTBF} \quad (4)$$

Choosing the maintenance type that will be implemented taking into account economic criteria, is achieved by calculating the ratio C_{pm} / C_{rm} as follows:

- if $C_{pm} / C_{rm} = 1$, then both types of maintenance are shown in one measure.
- if $C_{pm} / C_{rm} < 1$, then the preventive maintenance application is justified.
- if $C_{pm} / C_{rm} > 1$, then the reactive maintenance application is justified.

Any of these activities has a distinct effect on the components reliability and a corresponding cost based on necessary resources. The cost function includes repair costs, the cost of replacing worn-out parts, the cost of CNC machine tool downtime associated with production losses and the cost of repairs for accidental falls.

It is worth mentioning that there are no optimal maintenance costs. Instead, it is admitted that costs will decrease while costs for production losses are reduced. And the cost of production losses falls to the point where it is needed to stop the CNC machine tool more often for preventative maintenance and, as a consequence, the cost of the lost production starts to grow.

5. Consequence of Failure Analysis (CFA)

CFA is a method proposed in order to mediate between maintenance and CNC machine tools reliability, based on a technical and economic optimization, simultaneously addressing three issues:

- total cost of reinstatement if CNC machine tool fails.
- assessing the effect that maintenance has on reliability.
- behavior of elements subject to degradation over a period between two corrective actions.

Thus, maintenance (M) is a function that depends on three factors:

$$M = f(AF, RPN, FDP) \quad (5)$$

In the new approach, the concept is that a preventive maintenance action will apply only if it is proved that it is less costly than the failure. Thus, it is intervened on a component only if its replacement involves higher costs than maintenance.

The new method focuses on detection of non-critical components in financial terms, which should be isolated in preventive maintenance actions, in order to save financial resources and to free up as many human resources as possible. If maintenance tasks are prioritized correctly, maintenance costs can be reduced, also obtaining an optimum level of CNC machine tools reliability.

To validate the proposed method, the fault situations presented in table 4 are analyzed, from the results generated by FMEA method. At first, it is considered that all cases of failure involve a preventive intervention, in order of the rank they occupy in the priority list, rank 1 being the highest priority.

If one considers the defect evolution in time, it can be concluded that the possibility of preventive interventions is limited only to items that $FDP > 0$.

Table 4. Addressing maintenance strategy after analyzing by CFA method.

No.	S	O	D	RPN	FDP	AF	CFA	Ranking FMEA	Ranking CFA
1	7	5	2	70	$FDP > 0$	$Cpm / Crm < 1$	Mp	13	12
2	9	4	6	216	$FDP \rightarrow 0$	$Cpm / Crm < 1$	Mp	4	4
3	8	6	7	336	$FDP > 0$	$Cpm / Crm < 1$	Mp	1	1
4	9	4	9	324	$FDP \rightarrow 0$	$Cpm / Crm = 1$	Mr	2	
5	9	4	9	324	$FDP > 0$	$Cpm / Crm < 1$	Mp	2	2
6	5	2	8	80	$FDP \rightarrow 0$	$Cpm / Crm > 1$	Mr	11	
7	5	3	5	75	$FDP > 0$	$Cpm / Crm < 1$	Mp	12	11
8	5	2	5	50	$FDP \rightarrow 0$	$Cpm / Crm > 1$	Mr	15	
9	7	7	5	245	$FDP > 0$	$Cpm / Crm < 1$	Mp	3	3
10	4	3	9	108	$FDP > 0$	$Cpm / Crm < 1$	Mp	8	7
11	5	3	8	120	$FDP \rightarrow 0$	$Cpm / Crm > 1$	Mr	7	
12	5	4	8	160	$FDP > 0$	$Cpm / Crm < 1$	Mp	6	6
13	7	4	3	84	$FDP > 0$	$Cpm / Crm < 1$	Mp	10	9
14	7	4	3	84	$FDP > 0$	$Cpm / Crm > 1$	Mr	10	
15	6	2	7	84	$FDP \rightarrow 0$	$Cpm / Crm > 1$	Mr	10	
16	4	7	3	84	$FDP > 0$	$Cpm / Crm < 1$	Mp	10	10
17	5	6	3	90	$FDP > 0$	$Cpm / Crm < 1$	Mp	9	8
18	4	4	3	48	$FDP > 0$	$Cpm / Crm < 1$	Mp	16	14
19	4	7	2	56	$FDP \rightarrow 0$	$Cpm / Crm < 1$	Mp	14	13
20	7	4	7	196	$FDP > 0$	$Cpm / Crm < 1$	Mp	5	5

But in all this algorithms, the decisive element is the financial analysis, through which there are exceptions to the above. So, we meet the following situations:

- The element at number 2 (S, O, D - 9, 4, 6) shows a high failure severity, which involves noticeable consequences on the whole CNC machine tool, and rapidly evolving defect, indicating that the machine should be prepared for a reactive intervention. However, the option of intervention with preventive action is the result of the financial analysis, which finds that the losses by accidental interruption considerably outweigh the cost of preventive maintenance action.

- In case of item number 4 (S, O, D - 9, 4, 9), although the severity of failure is similar to element from position 2, the financial analysis finds that the production losses associated with the frequency of replacement the defective part has the same financial effects as in the case of applying a reactive maintenance. In this situation, the second option is adopted in order to free up the human and financial resources, to be used for another more critical situation.

- The result of the financial analysis is the decisive factor for the element at number 14, also.

Although the defect severity and its evolution in time indicates the need and opportunity to intervene preventively, the costs associated with reactive maintenance prove to be more advantageous.

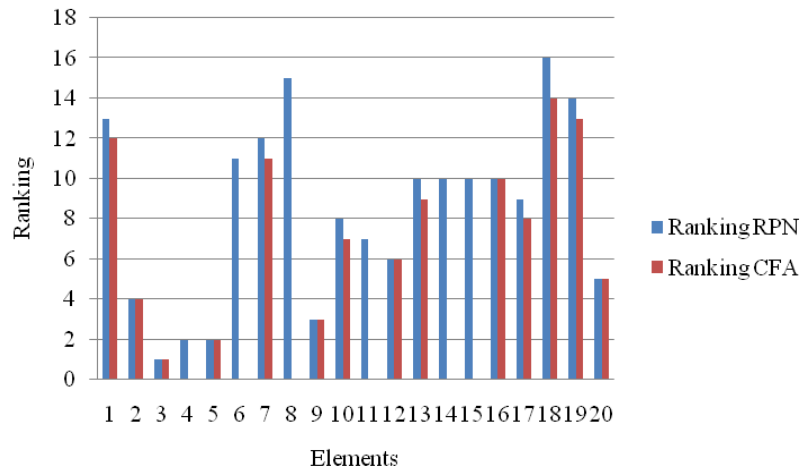


Figure 2. CFA and RPN comparative ranking.

After analyzing each situation of failure presented in table 4 by CFA method, it was found that 30 % of items do not require preventive intervention, as shown in figure 2.

6. Conclusions

The comparative calculation values, obtained for determining the priority ranking of the maintenance tasks by CFA method are complete and more realistic compared to the results of conventional FMEA. If only the RPN values are taken into account in prioritizing the maintenance tasks, then the highest level of reliability is obtained, but with high costs.

The minimum CNC machine tools reliability and maintenance costs are the main constraints considered in the CFA method.

By applying the new method, it was demonstrated that the implementation of a preventive maintenance is often financially unjustified. Applying this method on the given example shows that a reduction in maintenance costs can be obtained by reducing the number of preventive actions, while maintaining a minimum acceptable reliability level.

Judging the problem by the CFA method, it is found that to evaluate a CNC machine tool for planning maintenance actions, it is not necessary to spend time for evaluating critical components, which can be done later. First, it must be determined if preventive maintenance action turns out to be less expensive than the failure.

References

- [1] Doostparast M 2014 *Reliability Engineering and System Safety* **126** 98–106.
- [2] Remy E 2013 *Reliability Engineering and System Safety* **116** 8–19.
- [3] Kans M 2008 *Int. Journal Production Economics* **113** 734–47.
- [4] Carnero M 2006 *Reliability Engineering and System Safety* **91** 945–63.
- [5] Chang K H, Chang Y C and Lai P-T 2014 *J. Intell. Manufacturing* **25** 1413–27.
- [6] Sharma R K and Sharma P 2015 *Journal of Industrial Engineering International* **11** 253–68.
- [7] Ungureanu A L, Stan G and Butunoi P A 2015 *Applied Mechanics and Materials* **809-810** 1504-09
- [8] Bevilacqua M and Braglia M 2000 *Reliability Engineering and System Safety* **70** 71–83.
- [9] Dwight R 1999 *Journal of Quality in Maintenance Engineering* **5** 258–75.
- [10] Ingwald A, Kans M and Al-Najjar B 2004 *Proceedings of the Fifth IMA International Conference on Modelling in Industrial Maintenance and Reliability* 121–26.
- [11] Pujadas W and Chen F 1996 *Computer & Industrial Engineering* **31** 241–44.